# NASA ROVER AND TELEROBOTICS TECHNOLOGY PROGRAM

**C. R. Weisbin**
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099

**D. Lavery**
Office of Advanced Concepts and Technology
NASA Headquarters
Washington, DC 20546

## Abstract

This paper summarizes salient activities within the NASA Telerobotics Program, emphasizing complete telerobotic system prototypes which have been built and tested in realistic scenarios relevant to prospective users. The paper also describes complementary developments in innovative component technologies.

## 1. INTRODUCTION

The Telerobotics Program responds to opportunities of NASA space missions and systems, and seeds commercial applications of the emerging telerobotics technology. The primary goals of the program are:

> *Develop, integrate, and demonstrate the science and technology of remote telerobotics leading to increases in operational capability, safety, cost effectiveness, and probability of success of NASA missions.*

> *Develop and demonstrate the required technology so that by the year 2004, 50% of the EVA-required operations on orbit and on planetary surfaces may be conducted telerobotically.*

The scope of the program ranges from basic research, to synthesis of complete systems, and to evaluation in realistic ground and flight experiments. The emerging technologies have important dual uses both to NASA thrusts in space and in such commercial areas as medical robotics, agriculture, and subsea exploration. There is major participation by universities and industrial partners. This paper provides selected highlights of the technical achievements and future goals of the program. The Telerobotics Program is an element of NASA's ongoing research program, under the responsibility of the Office of Advanced Concepts and Technology (OACT).

The Telerobotics Program has been structured to address the three specific application areas: on-orbit attached and free-flying servicers, science payload tending, and planetary surface robotics. Within each of these areas, the program supports the development of robotic component technologies, development of complete robots, and implementation of complete robotic systems focussed on the specific mission needs. The program structure is summarized in Fig. 1.

**A. On-orbit Servicing:** This segment of the program develops technology for application to on-orbit satellite servicing by both free-flying and platform attached servicing robots. The target applications include such tasks as repair of free-flying small satellites, ground-based control of robotic servicers, and servicing of external space platform payloads. The user community includes Space Station Freedom, Mission to Planet Earth, and the Space Transportation System.

**B. Expiration Robotics:** This segment of the program develops robots to satisfy the planned requirements for exploring planetary surfaces. Robots will explore potential landing sites and areas of scientific interest, place science instruments, and gather samples for analysis and possible return to Earth. The robots required for such operations will require high levels of local autonomy, including the ability to perform local navigation, identify areas of potential scientific interest, regulate on-board resources, and schedule activities, all with limited ground command intervention.

Specific applications are to the Mars Surveyor Program and other programs planned by the Mission From Planet Earth user communities,

C. **Terrestrial and Commercial Applications:** This segment of the program provides a means to test and demonstrate space targetted developed technologies in realistic operational settings. In addition, this element of the program includes tasks intended to rapidly move program-developed technology out into the commercial applications community, These projects are jointly conducted by program laboratories and industrial partners to create and demonstrate full system prototype solutions to well understood terrestrial problems which can positively impact significant areas of the national economy.

D. **Component Technology:** This segment of the, program develops component technologies which address multiple user needs. These technologies are typically long lead-time items, which may take many years to fully develop and bring to an appropriate level of readiness. However, these elements typically have the potential of significantly improving or even revolutionizing the state-of-the-art in space telerobotics technology,

**E. Science Payload Maintenance:** This segment of the program matures robotics technologies for use inside pressurized living space to maintain and service science payloads. This capability will off-load the requirements of intensive astronaut maintenance of these payloads, and permit operation of the payloads during periods when astronauts may not be present.

# II. TECHNICAL OVERVIEW: ILLUSTRATIVE ACTIVITIES

## A. On-Orbit Servicing

### 1. Free-flying Servicers

Developing new technologies for space telerobotics brings with it the need to understand its impact on the operational capabilities of the eventual telerobotic systems. Addressing this area of space telerobotic operations is the primary focus of the University of Maryland Space Systems Laboratory (SSL). The SSL pioneered the development of analytical models for neutral buoyancy simulation and performed extensive tests on extra-vehicular operations, There has been intense emphasis on neutral buoyancy simulations of integrated EVA/telerobotic work sites. The Beam Assembly Teleoperator (BAT) has performed assembly of Space Station truss structures, as well as tests of Hubble Space Telescope servicing, both alone and in conjunction with EVA subjects. The Multimode Proximity Operations Device (MPOD) has performed a number of tasks relevant for orbital maneuvering vehicle-class spacecraft, and has demonstrated the utility of manned astronaut support vehicles for extended EVA capabilities. The Apparatus for Space TeleRobotics Operations (ASTRO) has been used to research three-dimensional positioning and station keeping systems. The Stewart Platform Augmented Manipulator (SPAM) replicates the functionality of the Space Shuttle Remote Manipulator System, with improvements in fine end-point positioning based on the Stewart Platform wrist. The Supplemental Camera and Maneuvering Platform (SCAMP) provides operator-controllable external video views, and has been used for tests of single-operator control of multiple free-flying telerobots.

The RANGER Telerobotic Flight Experiment (TFX) is under development at the University of Maryland Space Systems Laboratory. This project includes the development of neutral buoyancy and flight prototypes for a class of low-cost expendable telerobots designed for research and servicing in space, beyond the space station orbit. The RANGER vehicle is based on a modular design, drawing both design experience and component technology from BAT, MPOD, and other previous SSL telerobot projects. The vehicle will be equipped with four manipulators: two 7-DOF (degree of freedom) arms for bilateral dexterous manipulation; a 7-DOF manipulator for grappling at the local worksite; and a 6-DOF arm that positions a pair of stereo video cameras for primary feedback to the remote operator. A second stereo video camera pair, mounted on the vehicle centerline, will provide a stable visual reference for free-flight maneuvering, as well as to ultimately feed an image into a vision system for autonomous vehicle docking. Figure 2 illustrates early operational testing of the neutral buoyancy version of the Ranger vehicle.

## 2. Attached Servicers

### a. Dexterous Orbiter Servicing System

The Dexterous Orbiter Servicing System (DOSS), being designed and built by a team led by the Johnson Space Center, is a dexterous manipulator for the Orbiter payload bay. It is a sidewall mounted robot that operates from a fixed base or from the end of the Remote Manipulator System (RMS). This arm will provide the crew and mission controllers with an alternative to EVA for performing payload bay operations. These activities include EVA worksite setup, payload operations, and many contingency operations (e.g., repairs). The DOSS is designed for repetitive flights and can be used as a baseline operational capability similar to the RMS. It can also function as a testbed for future telerobotic experiments. The DOSS will utilize many technologies developed within NASA's Telerobotics Program, including robot control from Langley Research Center, remote surface inspection from JPL, and ground operator control from JPL.

### b. Remote Surface Inspection

Complex space missions require routine and unscheduled inspection. The Jet Propulsion Laboratory is developing supervised inspection techniques for tedious tasks as an aid to the operator. The telerobotic system would perform inspection relative to a given reference (e.g., the status of the facility at the time of the last inspection) and alert the operator to potential anomalies for verification and action. One example might be for the inspection of truss struts for micrometeoroid damage and visible cracks (e.g. 0.20 cm long, 0.02 cm deep, and .018 cm wide in openings as small as 20 cm and inspection up to 60 cm deep inside the opening) on thermal radiator surfaces. Simulation of realistic dynamic lighting conditions is included. The baseline inspection task is to teleoperate a robotic arm which carries a pair of mini-wrist cameras. The operator uses a pair of 3–DOF joysticks' and can control the lighting to better view the scene. Additional cameras with pan/tilt zoom/focus control are controlled by the operator to observe the arm's motion and to inspect objects which are far from the arm. A local remote architecture is employed so that space and time distances can be effectively treated. Figure 3 illustrates a single operator in a full scale cupula mockup performing an inspection of a simulated Space Station truss structure.

## B. Exploration Robotics

### 1. Planetary Rover Technology Program

Rover technology enables extensive robotic exploration of selected areas of Mars or other planets. The rover technology base emerging from this program has enabled the MESUR/Pathfinder project microrover, currently planned for launch in 1996. An active research and development program aimed at significant capabilities beyond the

Pathfinder microrover is in place at JPL. This technology base will greatly expand the current Mesur/Pathfinder micro-rover performance in the areas of goal identification, increased vehicle mobility, intelligent terrain navigation with in-situ resource management, and manipulation of science instrumentation. The goal is to combine both research and system demonstrations to advance the state of rover technologies while maintaining flight program relevance. Specific goals over the next four years are: (1) autonomously traverse 100 m of rough terrain within sight of a lander; (2) autonomously traverse 100 m of rough terrain over the horizon with return to lander; (3) autonomously traverse 1 km of rough terrain with execution of select manipulation tasks; (4) complete science/sample acquisition and return to lander with over the horizon navigation. A series of rover vehicles are being used to conduct these tests. Typical of these is the Rocky vehicle shown in Fig, 4, which provides a microrover testbed whose six-wheeled design enables the vehicle to climb over obstacles.

The rover technology program is being implemented with extensive university and industrial involvement in such areas as sensor suites for long distance navigation on planetary surfaces; legged vs wheeled vehicle mobility; virtual environment operator interfaces; robotic grasping devices; and behavior based obstacle avoidance and fault-tolerance.

### 2. **Lunar Rover Demonstration (CMU)**

The Lunar Rover Demonstration program at Carnegie Mellon University develops and demonstrates a convincing, comprehensive mobile robot mission capability required for a NASA Lunar Rover Mission, and associated commercial interests. l-he project builds on a number of mobile robot prototypes (DANTE, AMBLER, etc.) developed over the last several years at CMU, and tested in harsh environments including Mt.

Erebus (Antarctica) and Mt. Spurr (Alaska). Figure 5 illustrates the DANTE vehicle which was tested at Mt. Erebus, Antarctica.

The CMU Autonomous Technologies Task supports the Lunar Rover demonstration thrust by developing innovative perception, rover configuration, and task-level control technologies, facilitating key capabilities for' mission oriented autonomy and reliability of operation in rugged, unstructured terrain. The Ames Research Center telepresence/virtual reality user interface is also being developed supportive of the Lunar initiative.

## C. Terrestrial And Commercial Applications

### 1. Ground Emergency Response Vehicle

The Jet Propulsion Laboratory is developing a teleoperated mobile robot enabling Safety and HAZMAT Team personnel remote access to sites where hazardous materials have been accidently spilled or released. This task is demonstrating the feasibility of using teleoperated robots in hazardous and dangerous environments, thereby protecting people from unknown dangers. An important aspect of the project is the close involvement of the JPL Fire Department HAZMAT Team which provides input for system modifications as well as operates and tests the robot. The primary mission of the robot is first entry and reconnaissance of an incident site which may require unlocking and opening doors, climbing stairs, and maneuvering in tight spaces. The robot can also aid in material identification using an on-board chemical sensor as well as aid in incident mitigating by, for example, deploying absorbent pads or closing a valve. Figure 6 illustrates the HAZBOT-III robot deployed in a simulated incident.

## 2. **Satellite Test Assistant (STAR)**

The objective of this task is to use telerobotics technology to assist engineers as they ground test satellites or spacecraft in the large Space Simulation Chambers at JPL. Inside these test chambers spacecraft are exposed to extremely cold temperatures, high vacuum, and simulated sunlight thereby approximating a space-like environment. This project develops and demonstrates a mobile, multi-axis, multi-camera, telerobotic inspection system that will be deployed inside the thermal/vacuum test chambers and provide test operators with live high-resolution mono and stereoscopic video and real-time infrared thermal imaging of the spacecraft article under test. This will augment and improve current test procedures. The STAR IR camera may also be employed to calibrate solar flux intensities across the entire chamber volume, The STAR design was validated by successfully undergoing more than 50 hours of rigorous thermal/vacuum testing in the 10-Foot Chamber in a joint test conducted with hardware being developed for JPL'S Cassini spacecraft.

## 3. **RTPS Robotic Tile Inspection System**

Ground processing of space vehicles is 'slow, complex and expensive. Telerobotic methods applied to ground processing tasks offer potential to reduce turnaround times and increase quality and safety. In this task, a mobile positioner is being developed by the Kennedy Space Center, in conjunction with Carnegie Mellon University (CMU), SRI, Langley Research Center, and Rockwell International. The task will demonstrate the ability of a semi-autonomous robotic vehicle to inspect surfaces of the shuttle thermal protection tiles for chips and dents, automatically record inspection information into the tile data bases, and rewaterproof lower surface tiles, as well as provide a reconfigurable/expandable system that could perform cavity and gap digitization, non-contact bond verification, and surface contour measurement, These processes are extremely labor intensive under the current manual approach. Introduction of robotics could make a significant difference in overall operational efficiency. Figure 7 illustrates the Robotic Tile Inspection System as conceived, operating in the orbiter workspace.

### 4. **Robot Assisted Microsurgery**

Public concern for improved health care, coupled with recent enabling technology advances in computer-based imaging and robotics, is stimulating a growing interest in robotically assisted surgery. Notable progress has been made in such conventional surgical practice as artificial joint emplacement. High dexterity surgery at small scale remains largely unaddressed. Through a cooperative NASA-industry commercialization effort, this project develops a dexterity enhanced master-slave telemanipulator enabling breakthrough procedures in microsurgery, The task will provide an integrated robotic platform for master-slave dual-arm manipulation over a one cubic inch work volume at feature sizes ranging 20-100 microns. Capabilities will include force reflection and textural tactile feedback. The resulting NASA robot technologies will be benchmarked in actual operating room procedures for vitreous retinal surgery.

### 5. **Agricultural Robotics**

Agriculture is a ripe, relatively unexploited application opportunity with uncommon advantages for commercializing mobile robotics technology. Over a billion tractor miles are driven annually, repeatedly over the same ground. Speeds are low, and precision is moderate. The terrain is mild, and proven navigation techniques apply. The goal of this CMU task is to develop, demonstrate and productive marketworthy controllers, positioners, safeguards, and task software specialized to the needs and constraints of commercial agriculture and related industries. Component technology results will be integrated onto a commercial agricultural harvester, and demonstrations will be conducted of automatically controlled harvesting operations to market relevant standards.

## D. Component Technologies

The program is developing a number of component technologies, which complement the demonstration-driven tasks. Examples of these component technologies are provided below.

### 1. Advanced Robot Joint Technology

This task, being performed at the Goddard Space Flight Center (GSFC), develops an advanced electromechanical joint with a goal of producing at least a four-fold improvement in size (volume/mass) and power/torque output. At the same time, it advances the state-of-the-art in controllability, safety, and reliability. The joint will be fundamental to all electromechanical devices including robots and scientific instruments and, as such, will upgrade all manner of NASA satellites, robots, platforms, and scientific instruments.

### 2. Capaciflector Camera

Closed loop control of docking and berthing mechanisms, such as robots, is currently lacking within the final approach of a few centimeters. Alternative proximity sensors require minimum standoff distances (cameras, laser range finders). The capaciflector camera, being developed by the Goddard Space Flight Center, allows capaciflectors to operate close together, providing multiple proximity data streams, and the potential for full 6 degrees of freedom (DOF) control. Currently, mechanical scanning is used to locate, align, and grasp objects for manipulation. This is time consuming and requires special algorithms to be written for each task. Using the capaciflector camera, and electronically scanning the scene, will reduce time and provide a more general, compact solution to the berthing and docking problem. This would be especially useful on the second Hubble space telescope servicing mission (a proposed robotically assisted flight in 1997) where highly dexterous tasks must be executed.

### 3. Telepresence/Exoskeleton

This JPL-led project augments telemanipulation capabilities through the development and evaluation of a unique force-reflecting master-slave exoskeleton anthropomorphic arm-hand system, with the emphasis on the use of EVA-rated tools and on minimum training requirements. There is also strong interest for the backdriveable glove as a physical therapy aid to rehabilitate stroke patients paralytic hands. Figure 8 shows the current version of the 4-fingered master/slave setup.

### 4. Redundant Robot Systems

The objectives of this program element are to perform research in advanced robotics regarding fault tolerant manipulator systems. For space operations, extraordinary reliability will be needed to protect space assets, and to ensure that robots are capable of physical task performance over long duration missions. The goal of the failure tolerance in manipulator design task is to develop a major testbed to treat failure tolerance in mechanical structures associated with robotics and computer controlled machines. This work is being conducted at the University of Texas at Austin (UT), under the sponsorship of the Johnson Space Center.

### 5. Multiple Interactive Robotics

The Aerospace Robotics Laboratory (ARL) at Stanford University is developing new concepts for the precise manipulation of objects in free space. The ARL is pursuing two fields of robotic manipulation: control of free–flying vehicle systems, and high-performance control of flexible manipulators. The control of free flying vehicle systems focuses on navigation techniques and the development of a supervisory task level interface for tasks such as assembly of structures using a team of free flying space robots. The area of flexible manipulators includes research in object manipulation by a flexible macro-mini manipulator, and adaptive control of manipulators with complex dynamic payloads. Figure 9 illustrates one of the Stanford free-flying robots operating above an air-bearing table.

## F. Conclusions

While the NASA Telerobotics program has built a record of substantial achievement, important technical and programmatic challenges remain, The ultimate goal of building autonomous robots that can significantly assist humans in space and that can with little direct human intervention explore remote planetary surfaces is ambitious.

Technical challenges for on-orbit robotics include development of automated operation of remote dexterous robots from the ground, compilation and concatenation of robot skills to reliably execute complex sequences autonomously, instrumented end-effecters for improved dexterity in repair tasks, Similarly, technical challenges for planetary surface robotics include real-time perception for autonomous identification of scientific goals, on-board placement of science payloads and rock coring, and autonomous navigation over long distances of lens of kilometers or more.

Programmatic challenges include building on recent successes (e.g. Mars micro-rover) in having the program's technology used by actual flight projects. This challenge is being addressed by stimulating user involvement in each of the program tasks, during all stages (i.e. inception to completion) of the task. The program has matured a significant number of telerobotic systems, including several that are ready for flight experimentation.

An important future goal is to broaden the range of applications of telerobotics in space. Emphasis on manipulators for servicing tasks and mobile robots for surface operations has resulted **in significant opportunities** for flight experiments and missions. Telerobotics technology can however enable a much broader range of missions (e.g. robotic devices for asteroid sample retrieval, remote deployment and construction of astrophysics observatory on the Lunar surface). Synthesizing new classes of robot configurations for such missions, and evaluating the corresponding benefits, is an important future challenge.

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## LIST OF FIGURES

Fig. 1. NASA Telerobotic Program Organization Structure

Fig. 2. RANGER Neutral Buoyancy Vehicle During Mobility Tests

Fig. 3. Supervisory Control of Inspection Robot

Fig. 4. Rocky Microrover Vehicle Testbed

Fig. 5. DANTE Legged Vehicle

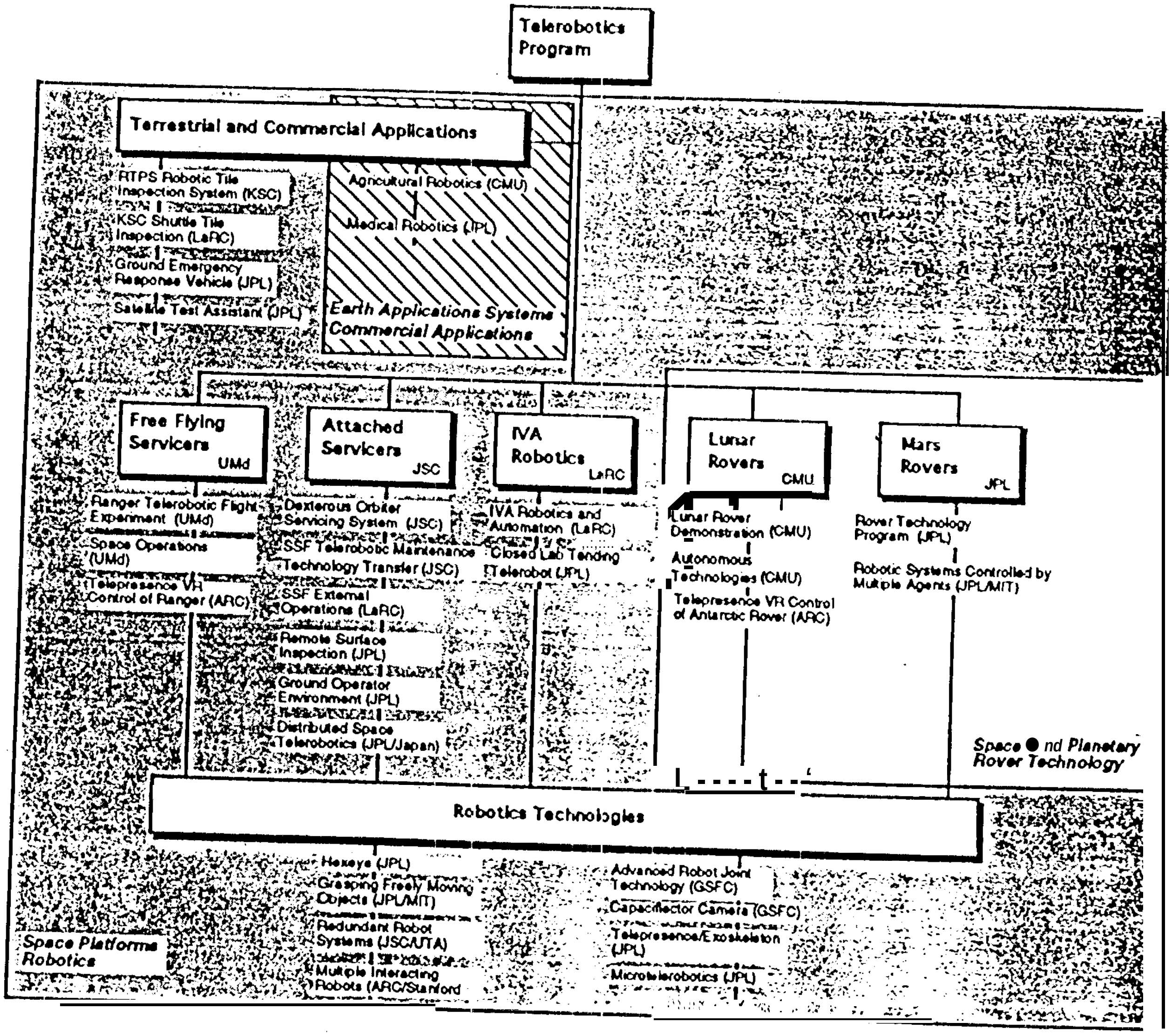
Fig. 6. Hazardous Operations Robot

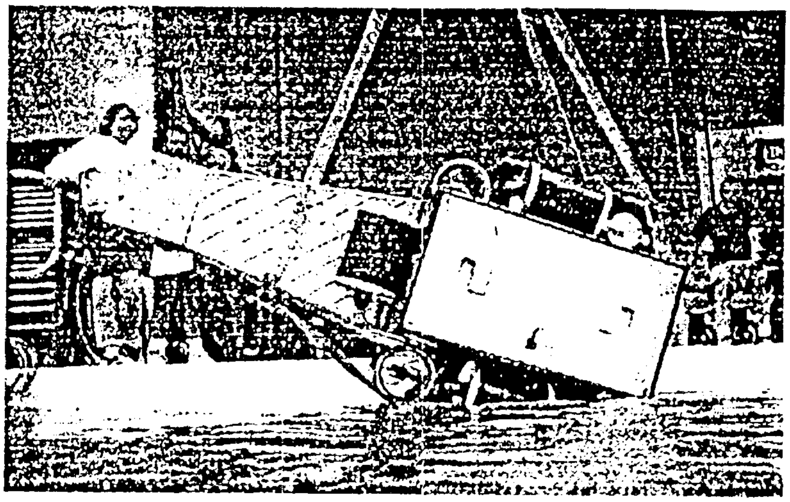
Fig. 7. KSC Tiie Inspection Robot

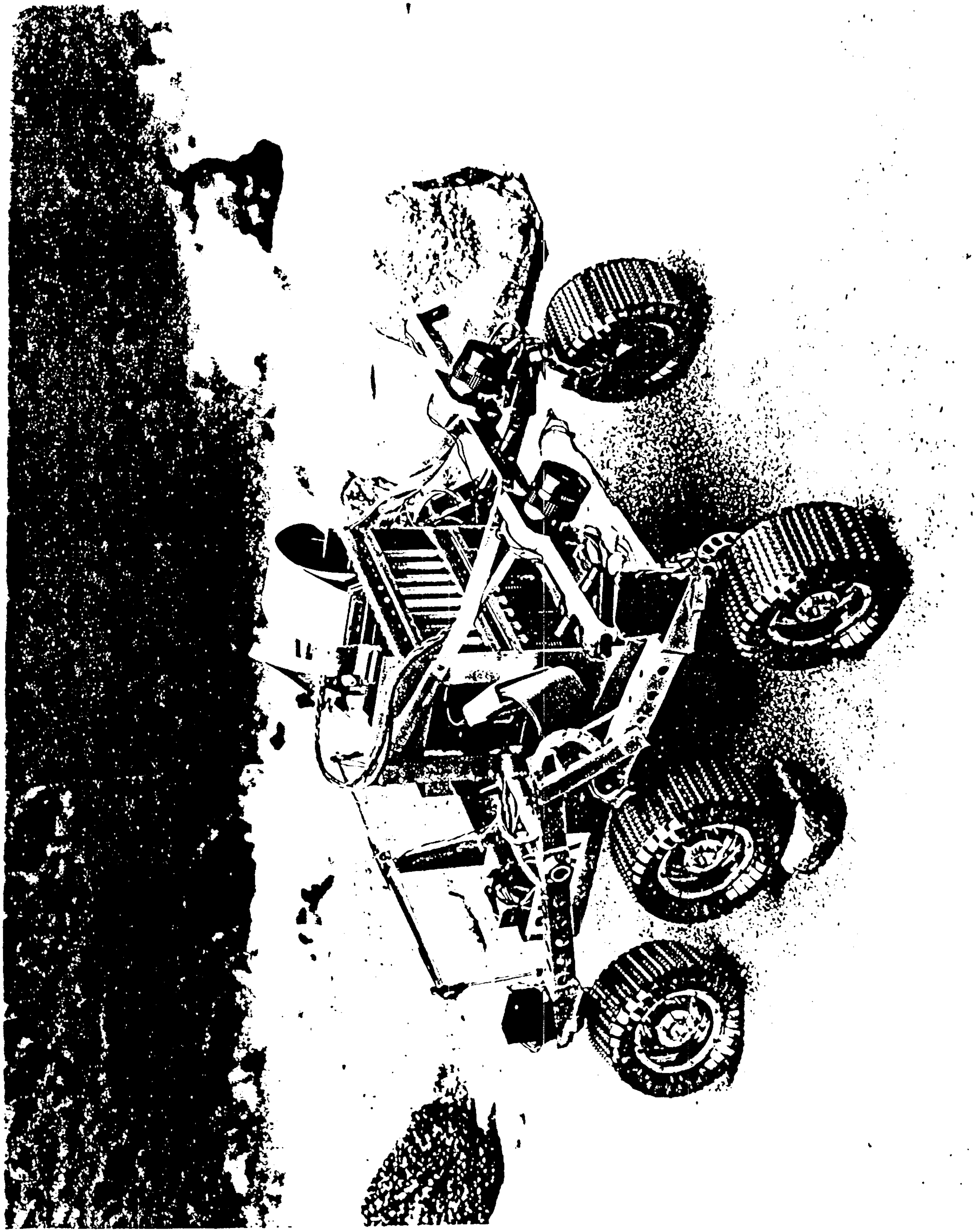
Fig. 8. Exoskeleton

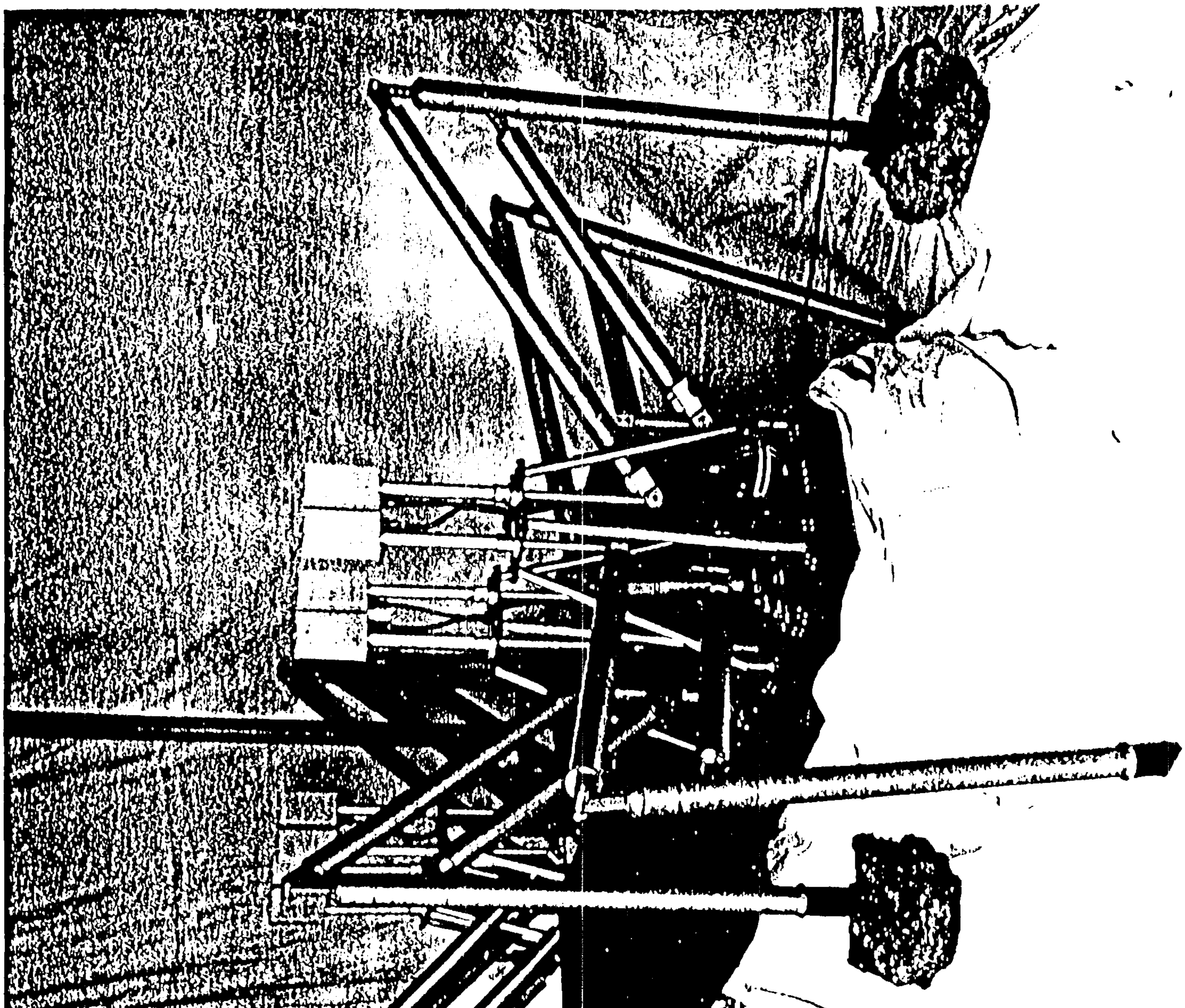
Fig. 9. Stanford Free-Flyer Operating Above Air-Bearing Table

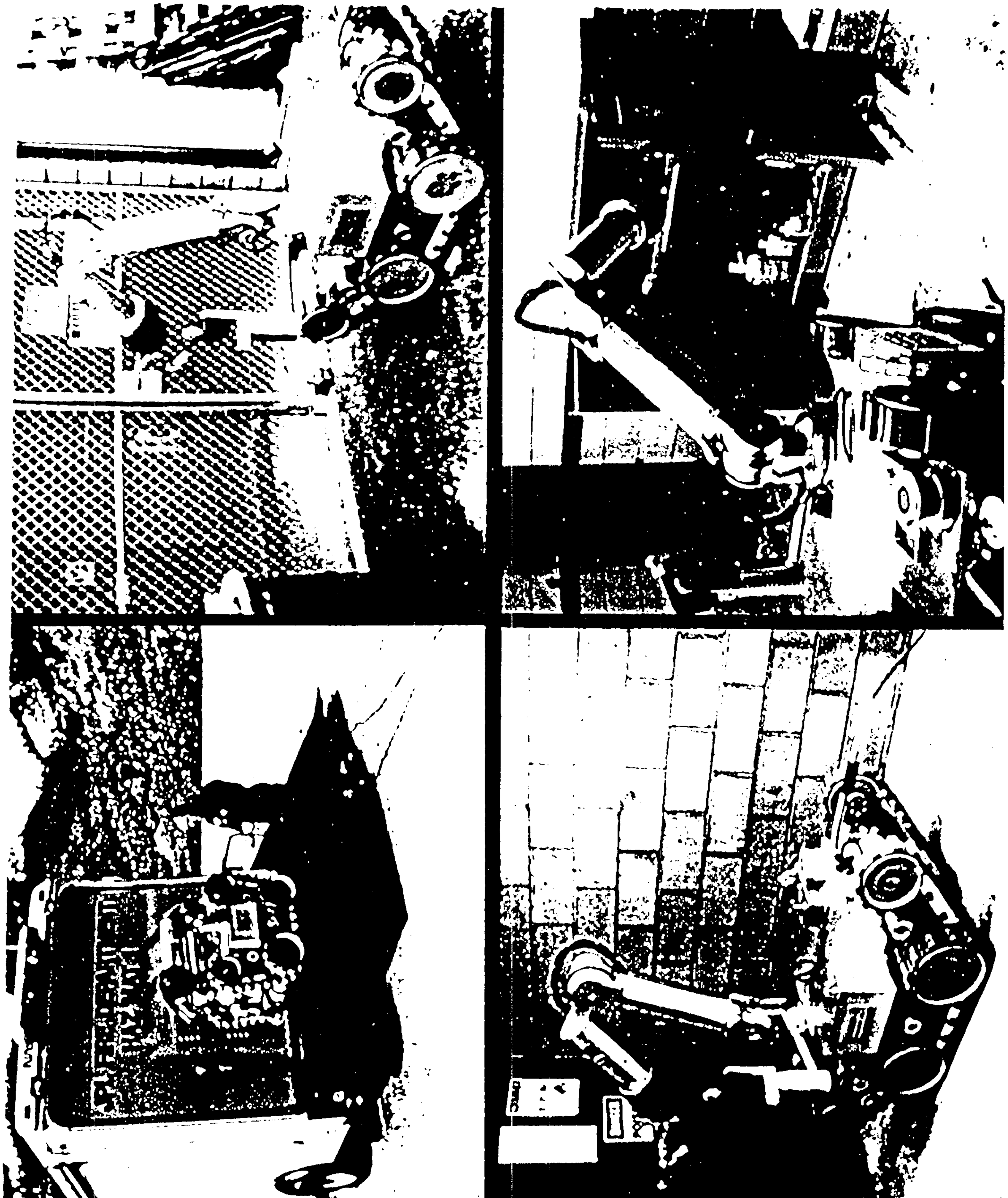
# TELEROBOTICS PROGRAM ORGANIZATION

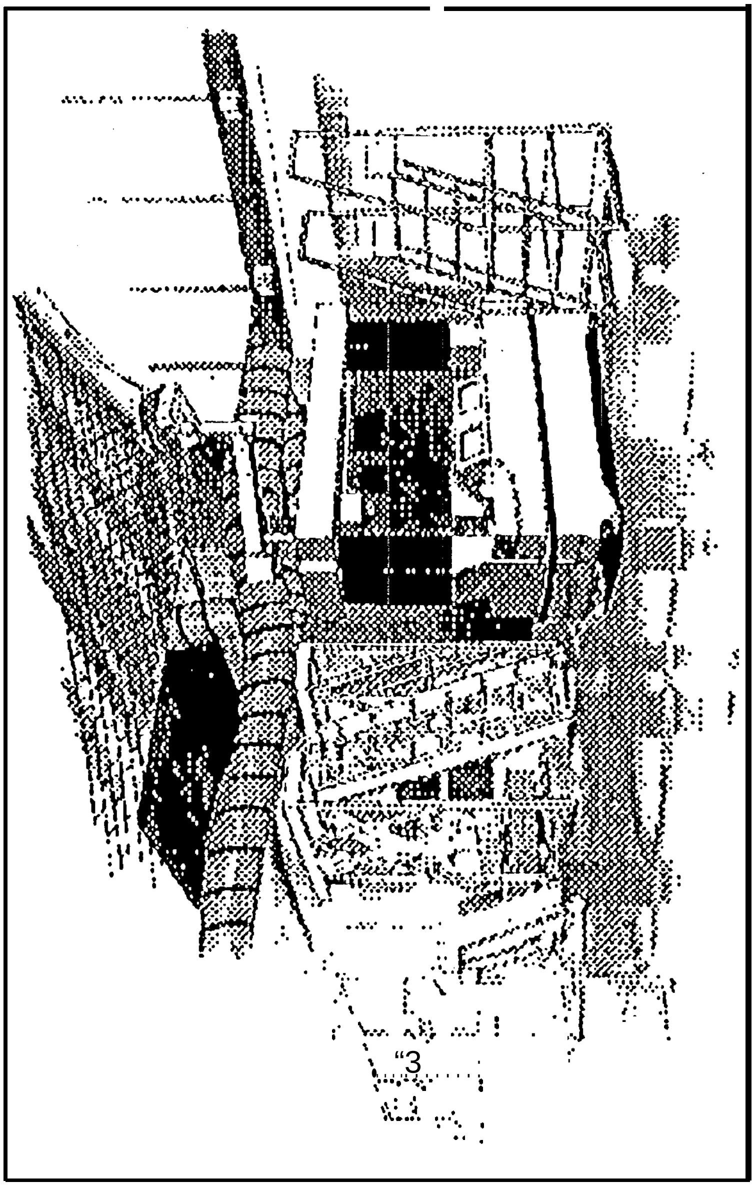


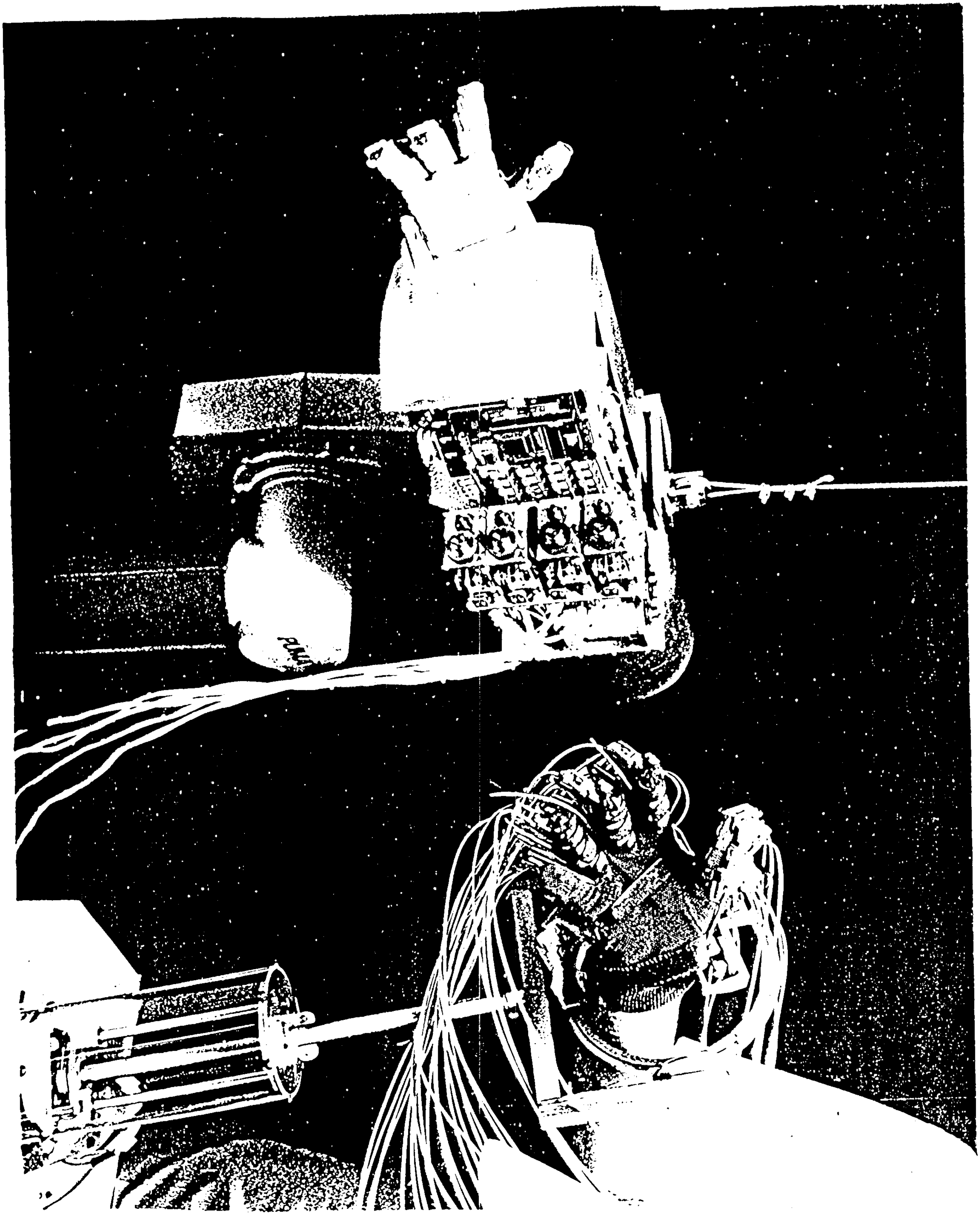


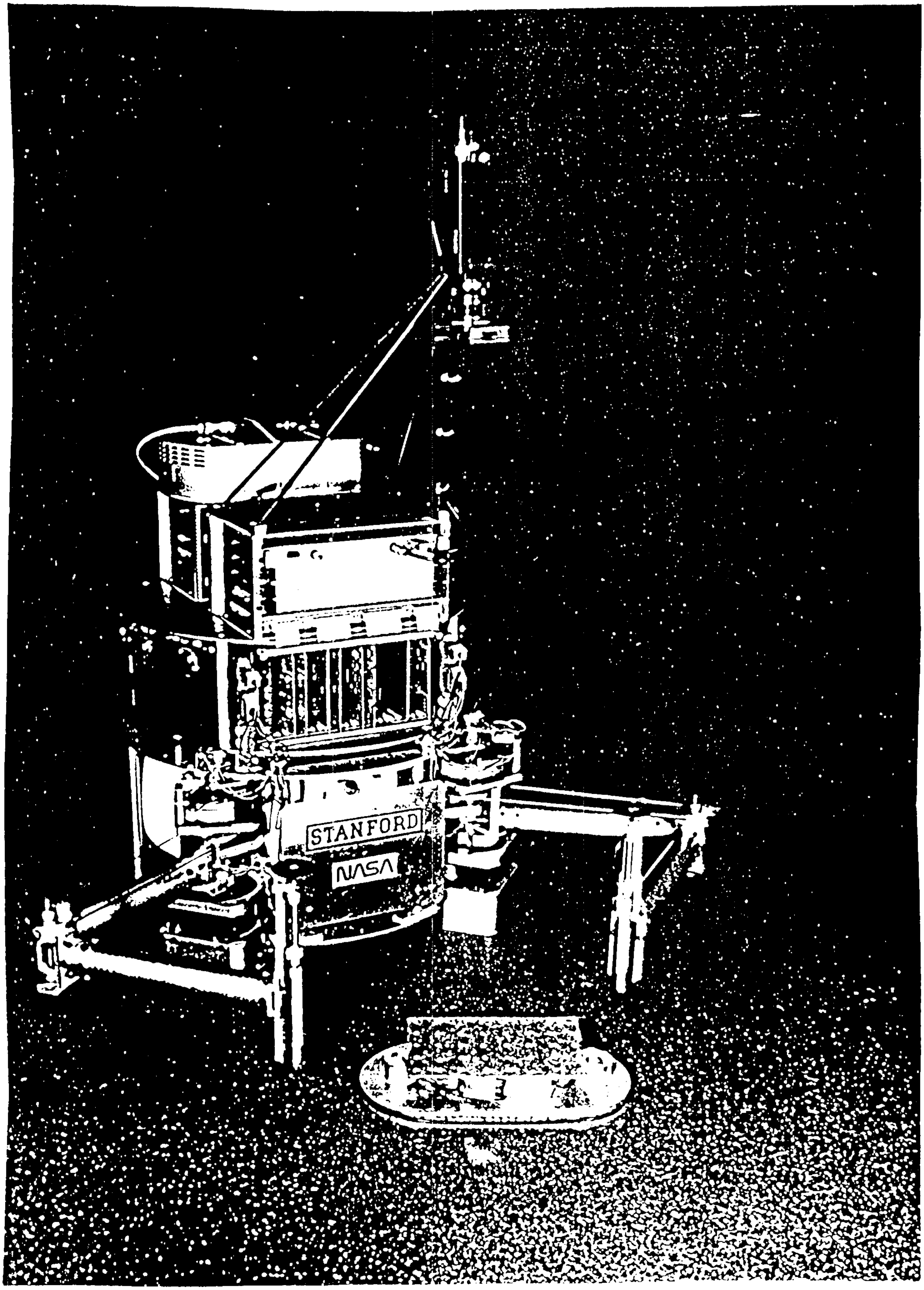








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